Journal of Urban and Environmental Engineering, v.13, n.2, p.317-328

ISSN 1982-3932
doi: 10.4090/ juee.2019.v13n2.317328

Journal of Urban and Environmental Engineering

www.journal-uee.org

MODELLING SYSTEM DYNAMICS TO EVALUATE URBAN WATER SUPPLY MANAGEMENT AND PRODUCTION OF FUTURE SCENARIOS

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Received 23 April 2019; received in revised form 16 September 2019; accepted 18 October 2019

Abstract: This paper analyzes, evaluates and simulates a water catchment and consumption process using a system dynamics model to support water resources management. After creating a theoretical model, real data from São Carlos in Brazil were used. The water availability situation was assessed using the catchment data analysis of the main surface and groundwater sources and the supply data, subdivided into four categories of use. Simulations were carried out by evaluating historical data and further simulations of future scenarios. The average annual consumption was 15.8 million m^3. The volume of water catchment in 2017 was more than 35 million m^3, and from this total 43.5% of treated water was wasted due to losses. Domestic consumption accounts for more than 80% of the total and greywater reuse can reduce this impact, which means economizing approximately 9 million m^3/year. Modeling allows decision makers to analyze the evolution of parameters and the scenario projection.

Keywords: Water supply management; System Dynamics Modelling; future scenarios.

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INTRODUCTION

Despite the false illusion of water abundance on the planet, the water resources available for urban supply is finite as much of this resource is not available for consumption. Approximately 97% or 1.3 billion km^3 is salt water and only 3 million or 42 million km^3 is freshwater. Moreover, 33 million km^3 of this freshwater is in the form of polar ice caps. Only 8.1 million km^3 remains as groundwater and 220 km3 as surface water for consumption considering all activities (agricultural, industrial, leisure, etc.) ~ 56,000 L / d (~ 20,000 m^3/year/person) (FAO, 2007).

Brazil holds almost one fifth of the world's water reserves, yet it suffers from scarcity due to irregular geographic distribution, degradation of areas around river basins, climate change and an inadequate supply of infrastructures (World Bank, 2016).

Increased water demand, depletion of available water sources and supply variability induced by climate change require increased water sources and the introduction of new policies in the current water management system. These measures should be evaluated for their economic, social, environmental, risk-based and functional sustainability to select the most sustainable options for a specific condition (Rathnayaka *et al.,* 2016).

After Forrester introduced the concept of system dynamics (SD) to model systems with complex feedback structures, the SD methodology found many applications, including water supply service management. According to Winz *et al*. (2008), the first to develop an SD model for the water supply system were Grigg and Bryson in 1975 in Fort Collins, Colorado, who sought to control the price of water while meeting the water demand of the growing population.

During the last 15 years, a significant number of studies have been carried out to support decision-making on urban water planning around the world and generally include simulation and modeling of parts or the entire urban water system. This trend is accompanied by the increasing complexity of urban water systems and the dynamic interactions that increase the uncertainty of water management decisions. These evaluations are often supported by methods such as multicriteria analysis (Rygaard *et al.,* 2014, Sapkota *et al.,* 2016), cost-benefit analysis (Mukheibir and Mitchell, 2015), life cycle assessment (Schulz *et al.,* 2012 , Lim *et al.,* 2010) and optimization techniques (Liner and Monsabert, 2011). However, few studies compare water supply options using available data (Moran, 2008). Most studies model the entire urban hydrological cycle to estimate the impacts of different water supply options on other components of the system (Bichai *et al*. 2005; Maheepala *et al*. 2004; Fagan *et al.,* 2010; Coombes and Barry, 2012).

Although these studies are significantly different in many ways, they have three common components: water supply and/or demand options, scenarios considered for these options, and evaluation criteria used to assess their sustainability. Scenarios are introduced to evaluate this performance in a variety of uncertainties that result from changes in the spatial and temporal variables of the system.

This work analyzes, evaluates and simulates the historical and future water catchment and consumption to provide an alternative for water management and policy makers to consider the estimated results of this study, to evaluate the sustainability of water resources management by evaluating historical data from 2008 to 2017 and by simulating future scenarios until 2028. It also considers the possibility of reducing consumption by reusing greywater and presents scenarios decreasing physical losses in the city's supply system.

Urbanization and Water Resources

The effect of climate change is widely recognized as a global issue, due to its impacts on urban water systems due to changes in rainfall regime affecting freshwater availability (Lenderink and Van Meijgaard, 2008; Hallegatte *et al*., 2011; Ranger *et al*., 2011; Willems *et al*., 2012).

A key factor influencing water availability and its quality is urbanization. Population growth without control contributes to increased nutrient loads and increased microbial flora (Maillard and Santos, 2008) and, therefore, according to Ghosh *et al*. (2014) urban areas have a high potential to generate negative environmental and ecological impacts at multiple scales. Thus, increasing water availability without affecting ecological systems is a major challenge (Breuste and Qureshi, 2011; Grimm *et al*., 2008).

Population growth, increased food production and industrial growth, as well as better living standards lead to an increased demand for water while climate change and environmental pollution affect the availability of water resources to meet this growing demand (Becker, 2013). Scarcity of traditional water sources, such as surface and groundwater, as well as the low efficiency of water use, are increasingly threatening the safety of urban, agricultural and environmental communities. The sustainable use of these water resources is increasingly important, as their mismanagement leads to serious financial, environmental and social problems. This context highlights the need to introduce alternative sources of water and demand management, and it is important to consider the sustainability of all these water sources.

Water losses

The losses are characterized by the difference in the volume of water produced and by that micro volume measured at points of consumption and can occur at any stage of a supply system, from the capture to the point of consumption. Considering the increase in water demand and water crises in many countries, this issue is relevant for all public or private water services (Schulz *et al*., 2012, Mutikanga *et al.,* 2009, Palme and Tillman, 2008).

Public water systems face a number of challenges, including aging infrastructure, increased regulatory requirements, inadequate quantity and quality. These challenges can be heightened by changes in the population and local climate.

According to the United States Environmental Protection Agency (USEPA, 2013), the United States will need to spend $ 200 billion over the next 20 years to improve its water transmission and distribution systems. From this amount, it is estimated that US $ 97 billion (29%) is needed to control water losses. The average water loss in American systems is 16%, and up to 75% of that amount can be recovered. While it requires investment in time and financial resources, loss management can be cost-effective if implemented properly. As water is one of the most valuable natural resources, water losses in the Water Distribution System (WDS) pose as an urgent problem that needs to be managed (Kanakoudis and Muhammetoglu, 2014).

Much of the drinking water infrastructure in urban areas has been in service for decades and can be a major source of water leakage. In addition to leaks, water can be lost through unauthorized consumption, administrative errors, data manipulation errors, and inaccuracies or measurement failures (Thornton *et al*., 2008). The International Water Association (IWA) and the American Water Works Association (AWWA) have developed standardized terminology and methods to help water systems track losses and conduct audits (USEPA, 2013):

- Real Losses - also referred to as physical losses are real losses of water from the system and consist of leakages from transmission and distribution mains, leakages and overflows the system´s storage tanks and leaking from service connections, including the meter.

- Apparent losses - also referred to as commercial losses occur when water that should be included as revenue appears as a loss due to unauthorized actions or miscalculation. Apparent losses consist of unauthorized consumption, customer measurement inaccuracies and systematic data handling errors in reading and billing meter processes.

- Non-Revenue water - is water that is not charged, and no payment is received. It may be authorized or result from apparent and actual losses.

In general, approximately 60% of total water losses comprise physical losses and the remaining 40% are responsible for apparent losses (Muhammetoglu & Muhammetoglu, 2018). The International Water Association has advocated and promoted four basic leakage management activities to reduce leakage, namely: (i) pressure management; (ii) active leakage control; (iii) speed and quality of repairs and pipe asset management; and (iv) maintenance and renewal (Charalambous et al., 2014). According to Hunaidi *et al.* (2014) leakage management comprises four main components: (i) quantifying the total water loss, (ii) leakage monitoring, (iii) locating and repairing leaks, and (iv) pipe pressure management.

A World Bank study showed that approximately 45 billion m^3 of water is lost annually due to leakage accounting for 35% of the total water supplied. If half of this water was saved, 100 million people would have access to safe water without any additional investment (World Bank, 2006). Non-Revenue Water (NRW) has negative environmental impacts (loss of water and energy) and economic (loss of revenue). Water losses imply greenhouse gas (GHG) emissions since the volume of water being lost is pumped, treated and distributed using energy. GHG emissions related to water losses are even greater when desalination is used as the main water supply process (Kanakoudis and Muhammetoglu, 2014).

The main benefits of reducing water losses are to minimize water pumping and treatment costs, increasing revenue, delaying investments in new water catchment and supply infrastructures, postponing the need to search for new water sources and reducing the risk of disease. The reduction of non-physical losses allows the increase of financial revenue, which increases the efficiency of the service provider, while reducing physical losses reduces production costs, reducing energy consumption. Thus, existing resources can be improved to increase supply without necessarily expanding the production system (Fontana and Morais, 2016).

Water reuse

Wastewater reuse is a common practice in developing countries in Asia and Africa, and wastewater recycling is common in regions with water scarcity in developed regions, such as Australia, the Middle East, the Southwest of the USA, and in places with severe restriction disposal on treated effluents such as Florida, coastal or inland areas of France and Italy, and densely populated European countries such as England and Germany (Marsalek *et al*., 2002). Even in high rainfall countries, such as Japan, where annual rainfall is 1,714 mm, urban wastewater reuse is common because of the high population density in some regions that suffer from water scarcity (Ogoshi, Suzuki, and Asano*,* 2001). Developed countries have developed techniques and guidelines for the safe reuse of effluents, which can be adopted by developing countries. After reviewing many recycling projects abroad, Radcliffe (2004) concluded that, worldwide, water reuse is becoming an increasingly common component of water resource planning as wastewater disposal costs and opportunities for developing conventional water supply**.**

Reclaimed water is the process of converting wastewater into water that can be used for other purposes. Reuse may include irrigating gardens and agricultural fields or replenishing surface water and groundwater recharge. Reuse water can also be targeted to meet certain needs in households, such as sanitary discharges, businesses and industries, and can even be addressed to meeting drinking water standards (Warsinger *et al.,* 2018).

Reuse instead of freshwater supplies may be a water-saving measure (Bischel *et al.,* 2013) and is a long-standing practice used for irrigation, especially in arid countries. Reusing wastewater as part of sustainable water management remains as an alternative source for human activities. This can reduce scarcity and relieve pressures on groundwater and other natural water bodies (Andersson *et al.,* 2016).

The World Health Organization (WHO) recognized the following as key drivers for wastewater reuse (WHO, 2016; WWAP (2017): increased water scarcity and stress; expanding populations and food safety issues; increased environmental pollution due to the inadequate disposal of wastewater and more recognition of the value of wastewater and greywater resources. For Burgess *et al* (2015), the need for reuse heightens as the world population becomes increasingly urbanized and can be an alternative water supply option.

Most uses of reclaimed water are for non-potable purposes such as car washes, toilet flushes, cooling water for power plants, concrete mix, artificial lakes, irrigation for golf courses and public parks. Where applicable, the systems operate with a dual piping system to keep recycled water separate from potable water.

System Dynamics Methodology

System Dynamics (SD) was introduced in 1961 when Jay Forrester published the book “Industrial Dynamics”. Since then, this field has expanded to include researchers and practitioners from the most diverse areas of knowledge, such as medicine, economics, sociology, military planning, and business domain (Shen *et al*., 2009, Rasmussen *et al*., 2012) . Historically, SD integrates three fields of knowledge: 1) control engineering and the concepts of feedback and self-regulation; 2) cybernetics and the role of information in control systems; 3) the theory of decision making in human organizations (Georghiou, 2001). According to Park, Sahleh, and Jung (2015), the characteristics of the systemic approaches adopted in systems theory were well presented by Beard (1999), in which 14 systemic ideas were provided, in which each idea was explained in terms of the associated philosophical concepts.

The methodology can facilitate the understanding of a system by extracting structures essential to its working mechanisms and, based on an analysis of the feedback structures inherent to the system, leads to the development of efficient management strategies. The main premise of this approach is the fact that the behavior of a system is determined by its internal structure (Richey *et al.,* 2014; Erkoyuncu *et al.,* 2011). Therefore, using its own language to model a system, its behavior can be investigated over time; that is, to test the different types of behavior that the real system can experience, making it possible to identify and evaluate potential improvements by adopting one or more leverage points (Oyarbide, Baines, and Kay., 2003; Pye and Warren, 2007). It is a methodology that attempts to map systems, seeking to examine the interrelationship of their influences, seeing them in a systemic context and understanding them as part of a common process (Homer and Oliva, 2001; Freeman *et al.,* 2014).

According to the systemic perspective, from which SD is derived, most managers seek to solve organizational problems in a reactive way and focus on short-term events and solutions (Iandolo *et al.,* 2017). Commonly, the models are based on previous or pre-determined knowledge and experiences, as well as analyzing the problem in parts. However, the most in-depth form of problem solving is to identify the underlying causes of system behavior patterns, allowing these patterns to be modified through the structural understanding of the system (Han, Love, and Peña-Mora., 2013; Rumeser and Emsley, 2016). Unlike linear systems, in a System Dynamics, decisions are derived from information about the system. The decisions are converted into actions that interfere with the behavior of the system. When new information is generated, the impact of the previous decision on the system in question can be evaluated (Jahankhani, Pimenidis, and Hosseinian-Far *et al*., 2012). SD modeling is oriented to map the structure, through the simulation, verify the impact of the decisions, and test different policies and solutions for system operations. These procedures open up space for different types of SD applications within the scope of management.

The representation of dynamic and non-linear systems, a properly systemic language should be used, given that our Cartesian and linear language is insufficient and as language shapes the perception, a new language would bring new ways of thinking that would facilitate the understanding of complex dynamic systems (Coelho and Chaim, 2014).

Developed computational simulation models based on a system dynamics methodology comprise four basic components: inventories, flows, converters and interrelationships between them, graphically represented as arrows and mathematically modeled as the finite difference equations. The value of each component is calculated at each delta time (DT) for a simulation time period specified in a model, starting at the initial values of the stocks and based on the functional relationships between the components.

Causal loop diagram (CLD) and Stock flow diagram (SFD)

Causal diagrams are a qualitative structure based on systems that characterize the directions of a specific behavior. Logic loops are created between certain conductors, and polarities of positive (+) or negative (-) influence are added (**Fig. 1**). Assigning the polarity between each model variable allows the creation of a final CLD and is used for an SFD model.

In an SFD, additional converters need to be added to describe important formulas and parameters used to designate conductor influences. Since SFDs are inherently quantitative, it is necessary to numerically define each of the parameters of the model through formulas, direct numerical values or standardized graphical functions (**Fig. 2**).

METHODOLOGY

Modeling historical data and future scenarios

The model was developed using STELLA (Experimental Learning Laboratory with Animation) software. **Figure 3** shows the model used to create the scenarios and the equations used in the model. After creating the theoretical model, we used data provided by the municipality responsible for water management in the city of São Carlos, São Paulo state, Brazil. Equations 1 to 5 were used to construct the model.

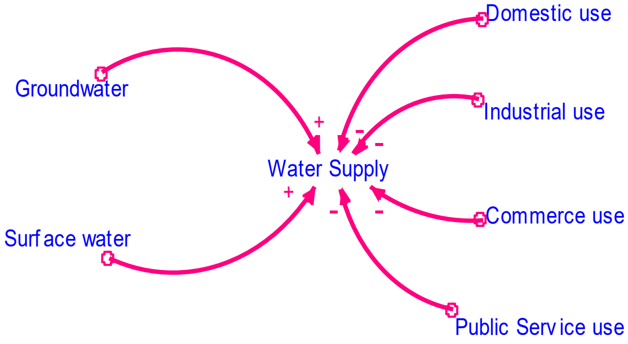


Fig. 1 *LCD*

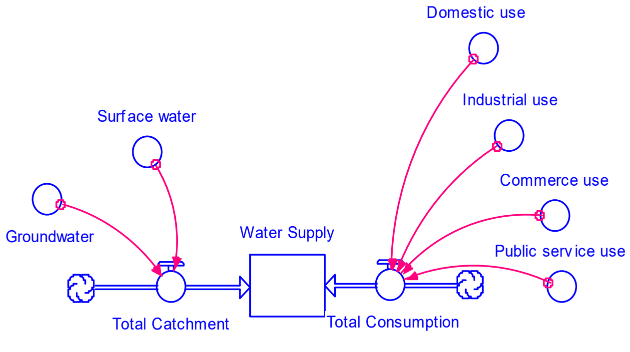
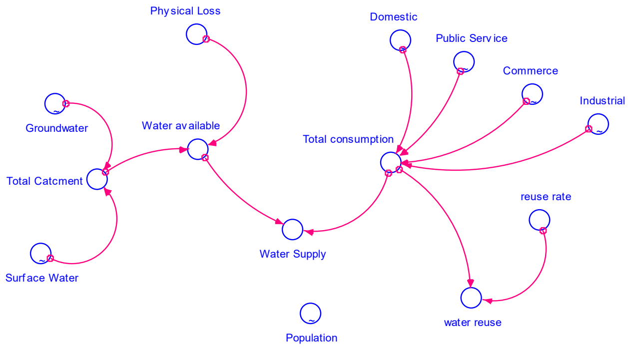


Fig. 2 *SFD*



$$\text{Total\_Catchment} = \text{Groundwater} + \text{Surface\_Water} \qquad (1)$$

$$\text{Total\_consumption} = \text{Commerce} + \text{Domestic} + \text{Industrial} + \text{Public\_Service} \qquad (2)$$

$$\text{Water\_available} = \text{Total\_Catchment} * (1 - \text{Physical\_Loss}) \qquad (3)$$

$$\text{Water\_reuse} = \text{Total\_consumption} * \text{reuse\_rate} \qquad (4)$$

$$\text{Water\_Supply} = \text{Water\_available} - \text{Total\_consumption} \qquad (5)$$

Fig. 3 Model and equations used to develop the real and future scenarios

Total Catchment is related to the sum of the total volume captured annually, since Total consumption is the sum of all the consumptions made by each of the categories throughout the year. Water available is given by the total volume captured minus the physical (variable) losses occurred in the supply system. Water reuse refers to the volume of greywater produced that has the potential to be reused and is given by the total consumption by the rate of reuse (variable). Finally, Water Supply is the actual available water subtracted from the total consumption in the city, that is, the difference between that produced and the water consumed annually. The data obtained for the analysis were population, catchment of groundwater and surface water and distribution and consumption of water in the city, using four strata of use: domestic; public services; commerce; and industry in the period from 2008 to 2017. Initially, the arithmetic averages were calculated of the variation rates of groundwater catchment (Grd), surface water (Sfw), domestic consumption (Dom), public services (Pub), commerce (Com) and Industrial (Ind) and population growth (Pop), for which the real values of each year were used, from Eq. 6.

$$\bar{X} = \frac{\left(\frac{n_2-n_1}{n_1}+\frac{n_3-n_2}{n_2}+\cdots+\frac{n_n-n_{n-1}}{n_{n-1}}\right)}{n} \qquad (6)$$

These values were used to calculate the projection of future growth of water consumption in the city. The averages obtained are shown in **Table 1.**

The above values were used for the projection of future growth, using the real value of the last year as the initial reference. Equations 7 to 13 below were used to obtain the future scenarios.

$$Pop\_2018 = Pop\_2017 + (Pop\_2017 \times 0.013) \cdots Pop\_2028 = Pop\_2027 + (Pop\_2027 \times 0.013) \qquad (7)$$

Table 1. Average growth rate of population, catchment and water consumption in the city of São Carlos.

Pop.	Grd	Sfwr	Dom	Pub	Com	Ind
0.013	0.060	-0.003	0.026	0.025	0.003	0.010

$$Grd\_2018=Grd\_2017+(Grd\_2017\times 0.060)\cdots Grd\_2028=Grd\_2027+(Grd\_2027\times 0.060) \tag{8}$$

$$Sfw\_2018=Sfw\_2017+(Sfw\_2017\ \times(-0.003))\cdots Sfw\_2028=Sfw\_2027+(Sfw\_2027\ \times(-0.003)) \tag{9}$$

$$Dom\_2018=Dom\_2017+(Dom\_2017\times 0.026)\cdots Dom\_2028=Dom\_2027+(Dom\_2027\times 0.026) \tag{10}$$

$$Pub\_2018=Pub\_2017+(Pub\_2017\times 0.025)\cdots Pub\_2028=Pub\_2027+(Pub\_2027\times 0.025) \tag{11}$$

$$Com\_2018=Com\_2017+(Com\_2017\times 0.003)\cdots Com\_2028=Com\_2027+(Com\_2027\times 0.003) \tag{12}$$

$$Ind\_2018=Ind\_2017+(Ind\_2017\times 0.010)\cdots Ind\_2028=Ind\_2027+(Ind\_2027\times 0.010) \tag{13}$$

Thus, future values from 2017 were obtained through scenario projections. The projections were made until 2028, however it would be possible to go further, if necessary.

The evaluation of the water situation of the municipality was carried out by analyzing the historical data of the catchment in the main surface and groundwater sources and of the supply data subdivided into four categories of use: public service; domestic; industrial; and commercial. The data was provided by the Autonomous Water and Sewage Service (SAAE) in São Carlos, the authority responsible for water resources management in the city.

In addition to these data, the reuse projection was based on the profiles of urban uses, in studies that mention the residential production of black waters around 30%, and the rest, greywater, can be recovered and reused (Moghadan, 2016; Randolph and Troy, 2008; Eriksson et al., 2002). The loss of water in the water supply system and its effect on the availability of treated water were also evaluated.

Characteristics of the Data Area

The study area covers the urban area of the city of São Carlos, which is located in the central region of São Paulo state, 230 km from the capital, between coordinates 47°30’ and 48°30' west longitude and 21° 30’ and 22°30' south latitude.

The municipality has a total area of 1,132km², of which 67.25km² corresponds to the urban area, about 6% of the total area (**Fig. 4**). According to the Brazilian Institute of Geography and Statistics (IBGE), São Carlos has a population of 246,088 inhabitants and a Municipal Human Development Index (MHDI) of 0.805 (IBGE, 2017). The territory of the city is situated in two watershed management units: 13 - Tietê-Jacaré and 9 – Mogi-Guaçu.

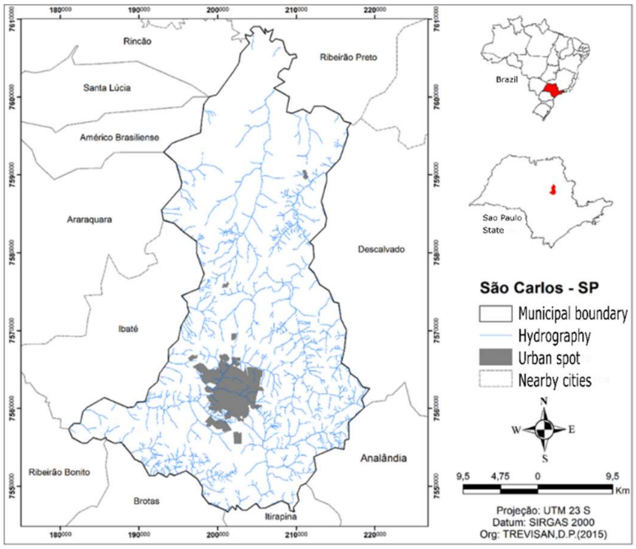


Fig. 4 Location of the municipality of São Carlos in São Paulo state and Brazil

The situation of water resources in the Mogi-Guaçu and Tietê-Jacaré Water Management Units, where the City of São Carlos is located, in relation to the balance between demand and surface and groundwater availability is considered critical, as more than 60% of the capacity is being used. The main uses of water are for irrigation and industrial use, followed by urban use (São Paulo, 2017).

According to the Ground Water Atlas of São Paulo state (*Atlas de Aguas Subterraneas do Estado de São Paulo*) (2013), Sao Carlos is in an area classified as a restriction, in which groundwater resources must follow specific guidelines for use and protection. One of the most important measures to be taken in restricted areas is to protect groundwater catchments intended for public supply. The municipality has a density of more than 1 well/km^2, according to the Atlas.

RESULTS AND DISCUSSIONS

According to data from the IBGE (2017), 96% of the population in São Carlos live in an urban area, a density of 210.7 inhabitants km2 and the municipality's growth rate is 10% compared to the last 2010 census, with a geometric growth rate of 0.94% per year. Table 2 shows the evolution of population growth in São Carlos from 2008 to 2017.

Regarding groundwater catchment, in addition to the 28 municipal wells used for water supply, the municipality has private wells registered in sugar cane areas (210 wells) and urban area (190 wells), and only 37 wells are protected by native vegetation (Mazzuco, 2018). The vulnerability of groundwater is evident in the absence of the protection of wells located in potentially contaminated areas due to the use of biological or chemical agricultural inputs and urban activities, such as industries and gas stations.

The reduction of the capacity of water sources also results from the suppression of the vegetal cover due to the intense use of soil by activities related to agribusiness, such as raising cattle, as well as sugar cane and orange plantations. It should also be emphasized that the environmental quality of a river basin is generally influenced by variables such as forest cover, road density, continuity of riparian forest and cultivation practices. The preservation of riparian forests directly influences the costs of treatment of the water abstracted. The cost to treat 1,000m³ can vary from US $ 0.52 in areas of preserved water sources to US $ 78.00 depending on the preservation of riparian forests (Tundisi, 2010).

The city is served by two surface springs: Ribeirão Feijão and Córrego do Monjolinho (Espraiado) and 28 deep groundwater wells. Some springs belonging to the Ribeirão Feijão water catchment area are located in São Carlos, which has 230 km² and is part of the Jacaré-Guaçu river basin. The vast majority of the Córrego do Monjolinho basin has regular and irregular urban occupations, which impairs its current quality and may affect its capacity to supply water in the future. The surface water sources are among the vectors of urban growth and in areas with intensive soil use due to intensive agricultural activities, that is, uses that require a large volume of water and are sources of pollution.

Using the data provided by SAAE, it can be observed that the largest volume of catchment currently takes place through deep wells. This is due to reaching the limited capacity of water sources for the water supply and the intense urban occupation and, consequently, the reduction of water availability (**Table 2**). Concerning the water supply (**Table 2**), even adding all other categories, the domestic category is the one that consumes the most (80%). Another important observation is that category consumption in general was very stable with few changes in volume during the period, except for the residential one that increased by 10% only in the last two years.

Considering that the real values are included in the model, the behavior of the supply system could be established in relation to the water supply for a growing population. In the graphs obtained as a result of the model, the actual values of 2007/17 and the modeled values of 2018/28 can be observed. The scenarios were created considering the population growth and the consequent increase of consumption and water abstraction. **Figure 5** shows the uptake behavior from 2008 to 2017 and the projection from 2018 to 2028, if the same management policy and the volume available after water losses in the system is maintained.

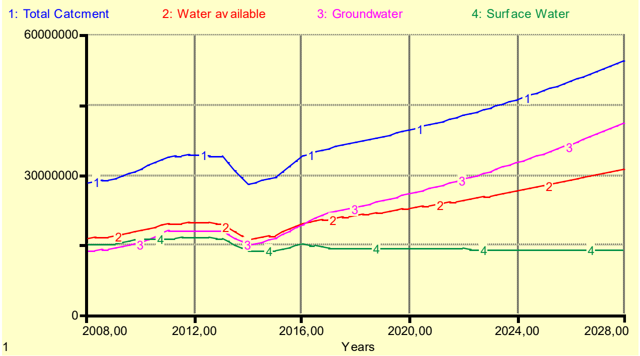


Fig. 5 Behavior of catchment and availability of water after losses.

The surface water catchment has been reduced due to urbanization and the proximity of the limited capacity of the sources. The banks of the Córrego do Monjolinho comprise an urban area of 4.2 km² representing 17.4% of an impermeable surface. In the Ribeirão Feijão Basin, new subdivisions emerged near the Washington Luiz highway (SP 310), including approved and registered land subdivision, as well as illegal subdivision, an increase in industrial concentration near the Luiz Augusto de Oliveira highway (SP 215), resulting in 10.9 km² or 4.9% of an impermeable surface in the Basin (Costa, 2013).

The increase in water catchment in the springs, mainly groundwater, coincides with the population growth in the same period and, consequently, increase in consumption.

The increase in the water catchment in the springs, mainly underground, coincides with the population growth in the same period and, consequently, increased consumption. According to Perroni and Wendland (2008) the recharge rate of the aquifer is around 100 mm/year in an area of 95 km2, generating a water availability in the order of 1099 m3/h and with a demand, at the time of the studies, of 2200 m3/hr. According to these data, the deficit would be 1183 m3/h, which shows that the exploitation of the aquifer is unsustainable, causing the level lowering at an average rate of 9 mm/year.

Regarding consumption, **Fig. 6** shows the annual consumption for the different categories in the period from 2018 to 2017 and the projection for the period from 2018 to 2028. It shows the population growth and increase in consumption. It can be observed that Domestic Use accounts for 80% of the treated water consumption.

Figure 7 shows the relationship between the population growth and increase in total treated water consumption. It can be observed that, as expected, that consumption is directly related to the population growth of the urban area of São Carlos.

Figure 8 shows the total consumption ratio; the total catchment, which is the sum of the groundwater and superficial catchment; the available water, which is the volume after subtracting the losses of 43.5% of the water treated by problems in the supply network; and the water supply, which is the difference between the available

Table 2. Real data of population growth, uptake and water consumption of the city of São Carlos.

Year	Population (hab.)[1]	Groundwater[2] (m^3)	Surface water[2] (m^3)	Domestic use[2] (m^3)	Public service use[2] (m^3)	Commerce use[2] (m^3)	Industrial use[2] (m^3)
2008	218080	13,197,656.31	14,793,373.75	11,117,041	463,000	1,731,061	709,562
2009	220463	13,849,723.39	14,893,176.53	11,313,988	460,837	1,421,942	630,695
2010	221950	15,006,918.55	15,858,311.50	12,188,412	331,388	1,585,662	725,762
2011	224172	17,041,603.17	15,907,619.00	12,357,478	446,566	1,627,840	714,406
2012	226322	17,771,711.61	16,209,271.12	12,904,863	605,341	1,755,589	657,834
2013	235457	17,674,328.26	15,982,958.00	13,062,658	676,922	1,709,785	580,339
2014	238958	14,399,121.37	13,165,465.53	13,021,692	643,133	1,776,647	789,706
2015	241389	15,879,558.12	13,297,985.00	12,696,444	439,188	1,660,783	729,146
2016	243765	18,961,461.40	14,694,978.00	13,553,209	473,884	1,651,585	780,071
2017	246088	21,388,407.04	13,932,764.00	14,046,186	465,000	1,731,061	709,562

water and total consumption. It can be seen that considering the losses at the current level, the available water, although positive, is very close to the limit, and it is even noticeable that during the São Paulo water crisis, consumption had to be reduced by rationing.

A real possibility of combatting the waste of treated water and reducing the impact of the catchment in the springs is the control of losses. **Figure 9** shows different scenarios of water loss rates in the water supply system. The first one described (number 1) is the loss in the supply system from the city of São Carlos of 43.5%, according to reports from the National Sanitation Information System (SNIS) (BRAZIL, 2016). The second (number 2) is the rate provided by the World Bank cited in a book called International Benchmarking Network for Water and Sanitation Utilities (IBNET), which conducted a study to estimate the performance of water operators regarding water loss. The average water loss was 35%. The third (number 3) refers to the average volume of 15%, which is considered low, and is used in countries where loss control is more effective, although it is above the values practiced in countries such as Germany and Japan of 10%. Finally, the fourth (number 4) refers to the goal established by the National Plan for Basic Sanitation (PLANSAB) (2013), which presents a set of targets to reduce losses by 2033. The value for the Southeast Region is 29% applying this scenario to the case of the municipality of São Carlos. It is possible to improve the availability of water without increasing the volume of direct catchment in the springs, and this reduction would save about 5 million m^3/year of treated water.

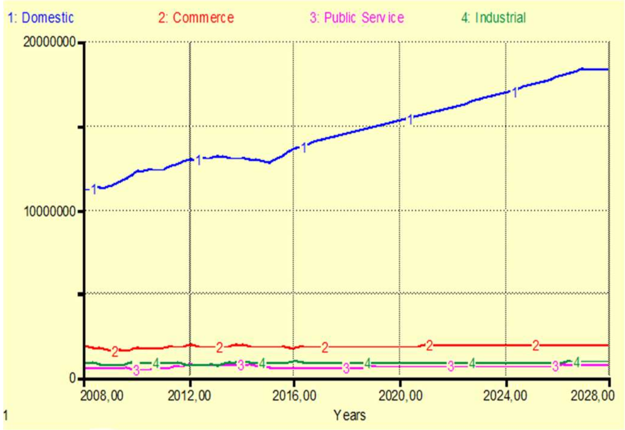


Fig. 6 Volume consumed by the different categories: domestic, commerce, public services and industrial.

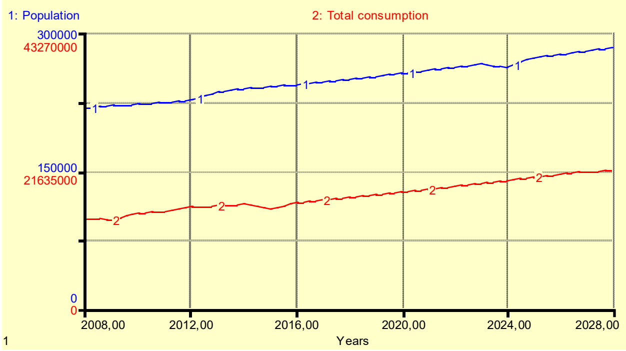


Fig. 7 Relation between population growth and water consumption.

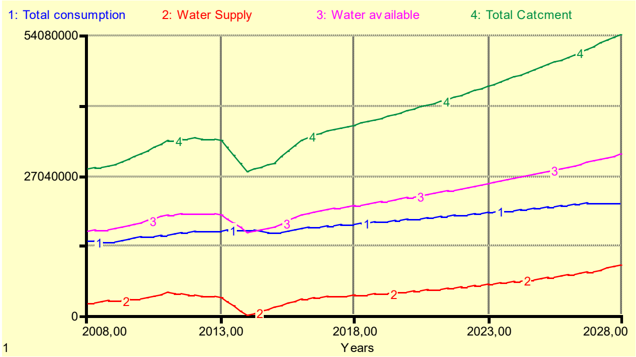


Fig. 8 Evaluation of the situation of treated water in the city of São Carlos, abstraction, consumption and availability.

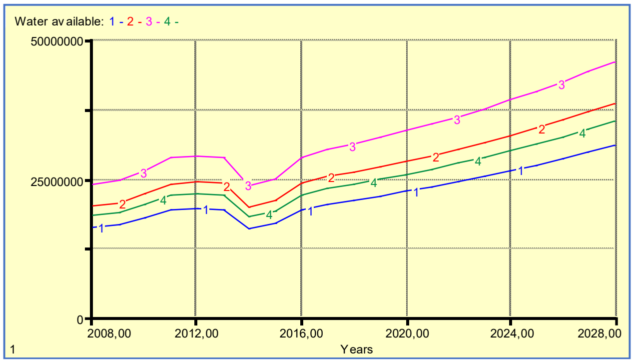


Fig. 9 Relation of the different rates of treated water losses in the system: (1) 43.5%; (2) 29%; (3) 15% and (4) 35%.

The quantification of all the lost water is obtained through a water audit in the whole system, through a water balance. Audits provide a valuable insight into the various components of consumption and loss, which are needed to assess the efficiency of a utility in relation to water delivery, finance and maintenance operations. In addition, water audits are required for planning other leakage management practices (Hunaidi et al., 2014). The extent of the actions and their results can be assessed by using scenarios.

Greywater reuse is a possibility to be considered as it is increasingly difficult to supply the population with water abstracted from springs. As an example of a shortage of water sources, the city of São Paulo has sought resources in increasingly distant river basins and in São Carlos the demand has been supplied with the increase of groundwater abstraction, a fact that is also unsustainable in the long term. In residential cases, greywater typically refers to wastewater from showers, bathtubs, bathroom basins, tanks, washing machines, but does not include wastewater from toilets, bidets and urinals, which is called blackwater. **Figure 10** shows the volumes of total water consumed by all categories. The quantity below the red line (line 2) is the volume that can be used to reduce treated water and can be used for different purposes, depending on the treatment.

According to Al-Hamaiedeh and Bino (2010), between 50-80% of sewage produced in a residence can be considered as greywater, thus a large volume of water consumed, mainly in residences, can be reused for other purposes. In the case of São Carlos, greywater reuse, considering only consumption and residential production, would achieve savings on treated water of approximately 9 million m^3/year. **Figure 11** shows the difference between the total amount of abstracted and consumed water with and without greywater reuse.

In the case of buildings, there can be a central system for collecting greywater, treatment and storage. In the case of residences, there may be an internal reuse system similar to that of buildings or a system to separate treated water, ash and blackwater. The responsible municipality would collect the greywater and redistribute it for non-potable purposes. This dual water distribution system was adopted in the Grand Canyon Village, Arizona, the USA in 1926 and treats and reuses about 3000m3/day (Eslamian, 2016). The positive balance between greywater production and water demand can provide financial savings and priceless environmental benefits (Couto et al., 2013).

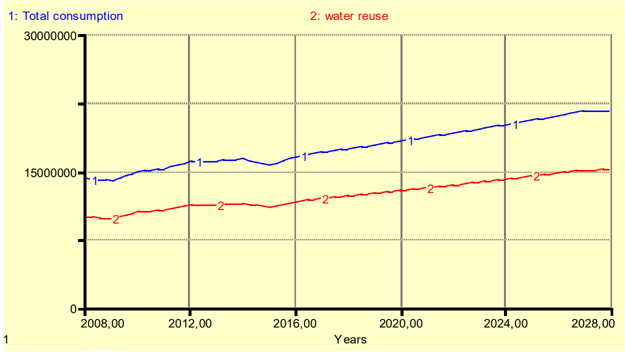


Fig. 10 Volume of greywater available for reuse.

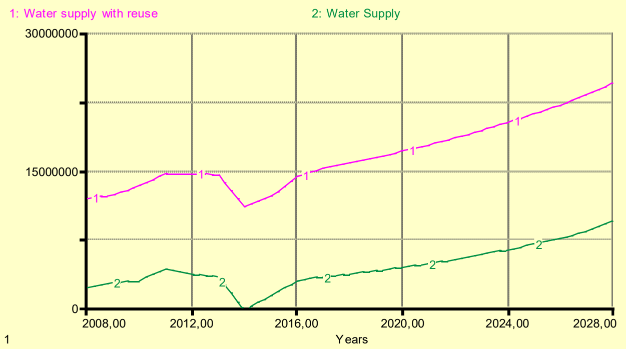


Fig. 11 Water availability with and without reuse.

CONCLUSION

The volume of water captured by São Carlos in 2017 was more than 35 million m^3. From this total volume, 43.5%, that is, 15 million m^3 of treated water was wasted due to physical or apparent losses. As mentioned previously, it is necessary to invest in combating waste and there are solutions for this. Even if the investment is high and long term, this resource cannot be lost, even more so if the post treatment cost is accounted for. In addition to the loss of resource, there is a high economic loss.

Unfortunately, the most simplistic solution is the option used in cases of increased demand, increased supply and overload of the catchment system. The best solution is still to economize to meet the needs of future consumption increases, and the best way to do it is to avoid waste and to made use of reuse for less demanding purposes.

Residential consumption accounts for more than 80% of total urban consumption and the greywater reuse can reduce this impact by up to 70%, i.e. an economy of approximately 9 million m^3/year, with a related financial saving. Surface water sources are at the limit and, with the increase in demand, the option used by the municipality was to increase the catchment of groundwater, causing a lowering of the aquifer. It can be observed that the increase in funding to supply the demand is not sustainable, so it is extremely important to take actions to reduce consumption in the medium and long term, since demand tends to increase proportionally to the population increase.

Scenario modeling enables decision makers to analyze the evolution of the catchment and consumption parameters from 2008 to 2017, as well as future projections of the same scenarios, including the possibility of water shortages due to exceeding the support capacity of the springs. Solutions, such as loss control and greywater reuse are essential to prevent the uncontrolled increase in water abstraction and preservation of water sources for the future.

Acknowledgment This work was partially financed and supported by the Coordination of Personnel Improvement. of Higher Education (CAPES), a foundation from the Ministry of Education (MEC). Brazil.

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